Horizontal Variability of Ocean Skin Temperature from Airborne Infrared Imagery

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LONG-TERM GOALS

The long-term goal is to understand the mechanisms that produce spatial variability over a wide range of scales in ocean surface skin temperature under low wind conditions.

OBJECTIVES

The first objective is to use an airborne infrared imager to produce both overview maps and high-resolution time series of thermal variability over the CBLAST study area. The second objective is to combine these data with measurements by other investigators to determine the extent to which horizontal variability in surface temperature is related to atmospheric and sub-surface phenomena.

APPROACH

The approach is to make airborne measurements of horizontal variability of ocean surface skin temperature during the CBLAST-LOW experiments using two complementary infrared (IR) sensors. An IR imaging system will provide high spatial and temporal resolution while a narrow field-of-view (FOV) radiometer system will provide calibrated surface temperature. The IR imager system will use up- and down-looking cameras in order to discriminate between real skin temperature variations and apparent variations caused by reflection from clouds. The high spatial coverage and fine spatial and temperature resolution of our systems will allow us to examine spatial scales in skin temperature from processes that span the atmospheric boundary layer of O(1km) down to wave-related processes O(1m). We will produce synoptic maps of temperature covering the CBLAST-LOW region at moderate altitude as well as observations of fine-scale structures. During flights we will transect between the tower and the offshore mooring sites at altitudes of 300 m to 1000 m. This will provide the opportunity to utilize the offshore tower (instrumented by J. Edson et al. - WHOI) and horizontal ocean buoy array (deployed by R. Weller – WHOI) data sets as well as directly compare sea-surface signatures with the oceanic and atmospheric boundary layer processes and fluxes. For the 2nd experiment in August/September of 2002 and recently completed the 3rd field campaign in July/August

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14. ABSTRACT
The first objective is to use an airborne infrared imager to produce both overview maps and high-resolution time series of thermal variability over the CBLAST study area. The second objective is to combine these data with measurements by other investigators to determine the extent to which horizontal variability in surface temperature is related to atmospheric and sub-surface phenomena.

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of 2003, we made measurements of the sea surface and the sky with down- and up-looking AIM model 640Q longwave IR imagers (512 x 640 pixels) and Heimann KT-15 radiometers. A Pulnix digital video camera was implemented to characterize the sea surface condition.

The down-looking IR imager was operated concurrently in two distinct modes—Point and High-Resolution Snapshot. Both modes obtain high spatial resolution and low noise temperature measurements. In the High-Resolution Snapshot mode, full images were acquired at 1 Hz in order to provide an instantaneous 2-D map of surface temperature with spatial resolution of less than 1 m and thermal resolution of roughly 0.02°C. In the Point mode, we sampled the IR imager at a fast frame rate (30 Hz) and then obtained a point measurement by taking the average of a subset of each image. Averaging of a subset of the 327,680 samples in each image reduced the noise and provided a high-resolution spot of the ocean surface. In this Point mode, the imager provided a time/spatial series equivalent to a "spot" measurement of temperature with a temperature resolution of less than 0.02°C and a spatial resolution of *O*(1-100m) depending on the altitude and selected image subset matrix.

WORK COMPLETED

We completed analysis on data taken during the CBLAST pilot experiment that occurred in July/August of 2001 and are presently submitting the results for publication. We analyzed data taken during the 2nd CBLAST experiment in August-September of 2002 from our newly-developed dual IR imager system on a Cessna Skymaster aircraft of Ambroult Aviation. A description of the airborne IR imagery system is given on the CBLAST-LOW website (http://www.whoi.edu/science/AOPE/dept/CBLAST/CBLAST%20IR%20Description.htm). We participated in the 3rd and final CBLAST experiment in July-August of 2003, mounting the same dual IR imager system on the Cessna Skymaster aircraft. The data have been cataloged and we are beginning to survey them for interesting features.

RESULTS

Contrary to the pilot experiment, we were able to take useful data during the day since the longwave imager minimized solar contamination of the IR imagery. The surveys in 2002 and 2003 quantified the horizontal mesoscale variability in the domain around the CBLAST-LOW site near the offshore tower and the horizontal ocean mooring/buoy array throughout the region extending 40-50 km offshore. The IR imagery shows high temperature variability on scales of *O*(10m – 1km). Operating the IR imager in Point mode offers a noise level that is significantly below that for an IR radiometer at all spatial resolutions. For example, at the nominal altitude for the 2002 campaign of 610 m, the KT-15 radiometer had a temperature resolution of 0.2°C and a spatial resolution of 80 m compared to 0.03°C and 2.3 m respectively for the longwave IR imager. Our IR system maps the regional SST variability within a 2-hour flight. Maps of sea surface temperature produced using the low-noise, high-resolution data from the longwave IR imager suggest that diurnal warming and tidal advection/mixing control the regional scales of SST. Results from the two weeks of flights in 2002 show that clear skies, strong insolation and moderate wind speeds lead to high SST variability (2.1°C in 10 km). The variability in SST is shown to diminish with the increase in overcast conditions and high wind speed events (1.5°C in 10 km). Repeated flights give us the capability to track the diurnal variability of ocean surface temperature and allow us to determine the extent to which ocean mixing, advection, or heat flux variability is driving this temperature variability.

We estimated the heat flux variability due to ocean skin temperature alone by implementing the TOGA COARE algorithm for the scalar fluxes. The standard expressions for the sensible and latent scalar heat fluxes are

$$
\begin{aligned}
Q_s &= \rho_a c_p C_h U_{10}(\theta - T_s) \\
Q_l &= \rho_a L_e C_e U_{10}(q - q_s)
\end{aligned}
\tag{1}
$$

where ρ_a is the density of air, c_p is the specific heat of air, U_{10} is the wind speed at 10 m, T_s is the ocean skin temperature, θ is the potential air temperature, L_e is the latent heat of vaporization, q is the water vapor mixing ratio, and q_s is the interfacial value of the water vapor mixing ratio that is computed from the saturation mixing ratio for pure water at T_s. The transfer coefficients for sensible and latent heat, C_h and C_e, are calculated using the TOGA COARE model [*Fairall et al.*, 1996]. Figure 1 shows a map of the sensible and latent fluxes calculated according to (1) using the map of T_s and the appropriate buoy data. The flight was in the late afternoon on August 22nd 2003 under variably cloudy conditions and a wind speed of 4 m s^{-1}. Figure 1 shows that the variability of the sensible and latent heat fluxes under low wind conditions was ±13.9 and ±52.8 W m^{-2} 10km^{-1}, respectively. Results from the two weeks of flights in 2002 demonstrate that the average variability of scalar heat fluxes was ±8.0 W m^{-2} 10km^{-1} for the sensible and ±36.1 W m^{-2} 10km^{-1} for the latent. The model input parameters (U_{10}, q, θ) were found to be relatively uniform within the CBLAST-LOW study site. Therefore, these results suggest that the heat flux variability is dominated by ocean skin temperature. Heat flux variability of this magnitude is important to the regional estimates of fluxes extrapolated from individual locations since regional flux estimates require an accuracy of better than 10 W m^{-2} [*Fairall et al.*, 1996]. This spatial heat flux variability is also important to the determination of the transfer coefficients since the spatial variability is integrated into the O(10km)-footprint of direct covariance flux measurements [*Edson et al.*, 1998].

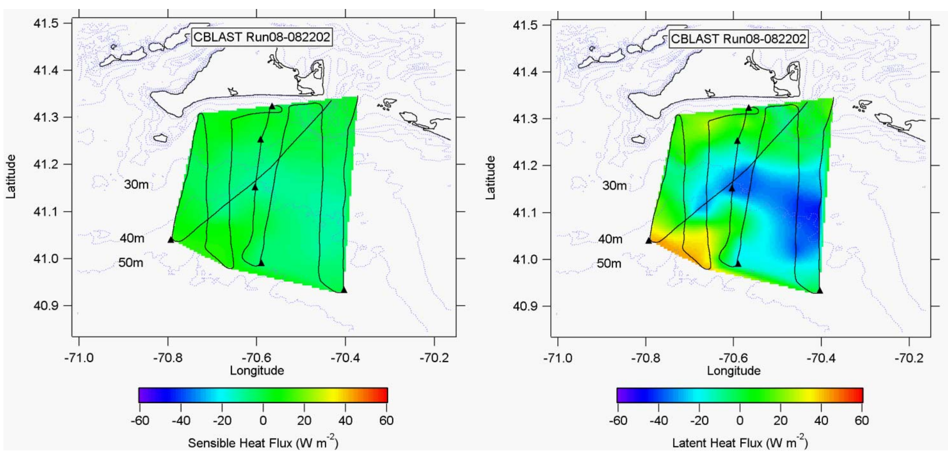
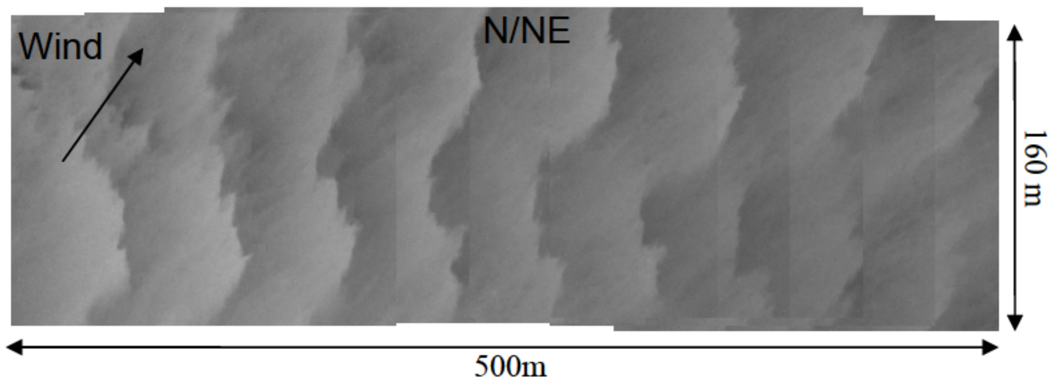


Figure 1. Maps of the sensible and latent heat flux variability determined using the sea surface temperature measurements produced using the low-noise data from the imager (in Point mode). The black trace is the Skymaster flight track.

Not only do we observe regional variability that is important to air-sea fluxes, but we also observe small-scale structures within the IR imagery (Snapshot mode operation) that suggest mechanisms that drive or enhance exchange under low wind speed conditions. The IR imagery shows high temperature variability on scales of O(10m – 1km). Figure 2a shows a mosaic of IR images that depicts successive temperature fronts. These data were taken at dawn on 8-22-02 in the late afternoon from an altitude of 600 m, which corresponds to a resolution for the imager of roughly 0.3 m. The wind speed was roughly 5 m s^{-1} and the direction was from the SW. An individual IR image is roughly 150 m x 200 m in scale, such that the mosaic is roughly 160 m x 500 m. Lighter shades of gray are warmer temperatures. The variability in temperature across these successive fronts in Figure 2a is of O(0.5 ºC)

and the spatial scale between the crests of the fronts are of 77.9 ± 16.6 m. The lack of coherent parallel features in the IR sky imagery suggests that the ocean surface features observed in the downward looking imagery in Figure 2a are, in fact, real temperature structures. Thorpe [1988] observed similar coherent structures during stable stratification and suggested the positive skewness was due to "billows" from shear-induced turbulence. Here, the spatial temperature variability is calculated to be 0.009°C m^{-1} and the skewness observed in Figure 2b is 2.8, which is significantly greater than that observed by Thorpe. The crests of these fronts are parallel to ubiquitous visible surface slicks. Comparison to the SCIMS data of N. Frew at WHOI show that the spatial scales observed in enhancement of ΔCDOM within the microlayer were comparable to those of the coherent ramp temperature structures observed in the airborne IR imagery. The relationship of microlayer enhancement to the coherent structures will continue to be explored.

a)



b)

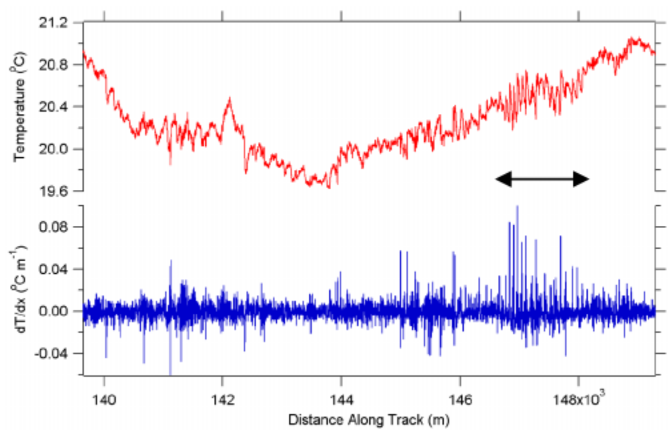
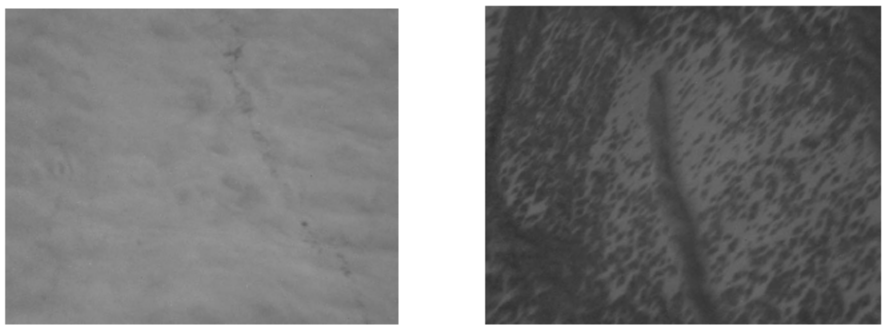


Figure 2. (a) Mosaic of IR images from Snapshot mode showing the successive fronts of ocean skin temperature in the presence of ubiquitous surface slicks observed on 8-22-02 during a period when the wind was 5 m s^{-1} from the SW. The top of the mosaic is NE. (b) Point mode temperature and its derivative measured along the flight track that correspond to the observations in (a). The black arrow denotes the region of the coherent ramp structures observed in (a).

We also observed fine-scale features within the IR imagery under very low to wind speed conditions. Figure 3a depicts two examples of the infrared signature that is produced during very low wind speeds. These data were taken mid-morning on 8-27-02 with a wind speed less than 1 m s^{-1}. Each image is roughly 160 m x 200 m. The infrared image on the left in Figure 3a shows minimal structure while that on the right shows significant spatial variability exhibited by the dark circular blotchy regions.

Figure 3b shows the temperature and derivative of the temperature along the track observed during the flight of the observed imagery in Figure 3a. For the region along the track depicted by the left image in Figure 3a, the spatial temperature variability is calculated to be 0.004°C m^{-1} and spatial scales of *O*(100m)while for the region depicted by the image on the right, the spatial temperature variability is calculated to be 0.013°C m^{-1} and spatial scales less than of *O*(10m). The overall skewness in Figure 3b was observed to be 0.06, suggesting that the temperature variability is Gaussian. This comparison demonstrates the broad range in scales of variability that exist under very low wind speed conditions.

(a)



(b)

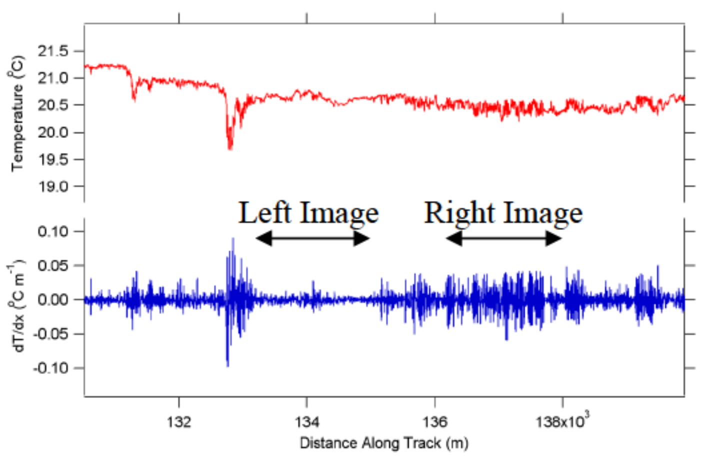


Figure 3. (a) Examples of fine-scale IR imagery as observed from the aircraft under very low wind speed. Each image is roughly 160 m x 200 m and the top of the images is West. (b) Temperature and its derivative measured along the flight track that correspond to the observations in (a).

We also observed the evolution of fine-scale features within the IR imagery during a moderate wind speed period. Figure 4a shows an IR image (top) taken on 8-28-02 when the wind speed was increasing to 8 m s^{-1} and the direction was from the NE. The image shows an ocean surface that is roughly uniform temperature with very thin bands of cool water that are parallel to the wind and roughly 0.05°C less than the broad regions between the bands. The spacing between these thin cool bands is 28.6 ± 10.2 m. Figure 4b shows the temperature and derivative of the temperature along the track observed during the flight of the observed imagery in Figure 4a. Here, the spatial temperature variability is calculated to be 0.005°C m^{-1} and the overall skewness was observed to be 0.07, suggesting that the temperature variability is Gaussian. These parallel-aligned structures are suggestive of Langmuir circulation and, to the best of our knowledge, are the first high-resolution airborne infrared measurements of the phenomenon.

(a) b)

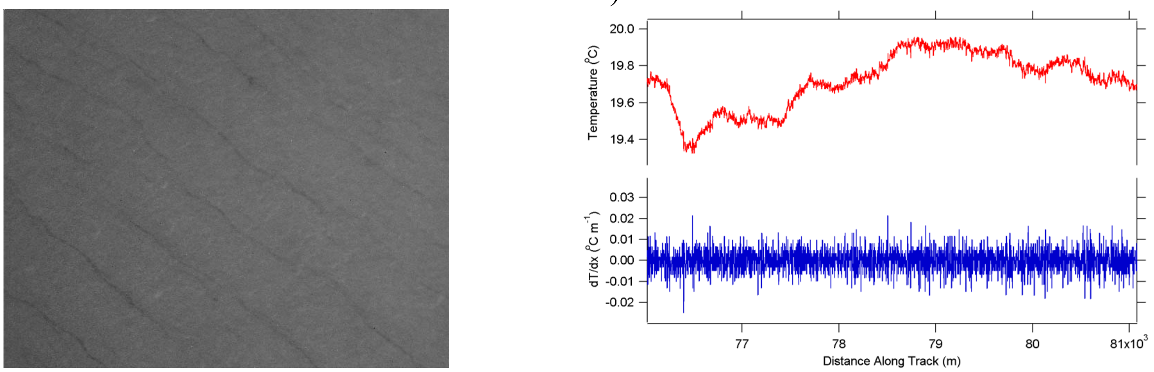


Figure 4. (a) Example of fine-scale IR imagery as observed from the aircraft under moderate wind speed. Each image is roughly 160 m x 200 m, the top of the images is East, and the wind is from the NE. (b) Temperature and its derivative measured along the flight track that correspond to the observations in (a).

We recently completed the 3rd field campaign over the CBLAST-LOW site in July/August of 2003 longwave IR imaging system aboard the Cessna Skymaster. Preliminary maps of ocean skin temperature are catalogued on the CBLAST-LOW website (http://www.whoi.edu/science/AOPE/dept/CBLAST/IR Aircraft.html).

IMPACT/APPLICATIONS

The encouraging results of our airborne deployments under the CBLAST DRI demonstrate that we are able to provide sea surface temperature measurements with high spatial resolution and accuracy. The impact of our analysis and observations will be to show that remote sensing techniques can quickly characterize the spatial and temporal scales of a wide variety of processes that are important to the air-sea fluxes, as well as to relate the fine-scale to the larger-scale variability.

RELATIONSHIP TO OTHER PROGRAMS OR PROJECTS

This project is in collaboration with A.T. Jessup of the Applied Physics Laboratory at the University of Washington. We are working closely with R. Weller of WHOI to correlate the IR signatures with environmental conditions measured by the buoys deployed during CBLAST.

REFERENCES

Edson, J.B., A.A. Hinton, K.E. Prada, J.E. Hare, and C. W. Fairall, Direct covariance flux estimates from mobile platforms at sea, *J. Atmos. Oceanic Tech*, *15*, 1998.

Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson, and G.S. Young, Bulk parameterization of air-sea fluxes for Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment, *Journal Of Geophysical Research*, *101* (C2), 3747-3764, 1996.

Thorpe, S.A., The dynamics of the boundary layers of the deep ocean, *Science Progress*, *72* (286), 189-206, 1988.